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A study of internal conversion coefficients of transitions in Pb^{205} and Pb^{206}

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With 7 figures in the text

1. Introduction

Using beta-spectroscopic techniques Schmorak *et al.* [1] and Fritsch [2] studied nuclear levels in Pb^{205} in the K-capture decay of 15 day Bi^{205}. The Pb^{206} nucleus was beta-spectroscopically investigated by Alburger and Pryce [3] in the 6.3 day K-capture decay of Bi^{206}. The level schemes of these Pb-nuclei were found to be very complex as is expected from the fact that they differ from the double-magic ${}^{126}_{82}Pb^{208}$ by 3 and 2 neutron-holes, respectively (cf. the theoretical calculations by Pryce for Pb^{205} [4] and Pb^{206} [3]). As a matter of fact, more than 30 gamma transitions were observed in each decay.

For the construction of decay schemes information about multipolarities of transitions is of very great importance. The quoted authors suggest multipolarities for some of the transitions in Pb^{205} and Pb^{206} on the basis of K/L ratios of conversion lines, conversion in L subshells, or relative gamma-ray intensities as estimated from scintillation spectra. Further information about the multipolarities of the transitions in Pb^{206} was recently given by Novakov *et al.* [5] who studied the gamma rays following the decay of Bi^{206} by the method of external conversion in uranium. Their relative gamma-ray intensities were obtained from observed photolines, and by combination with the relative internal conversion-line intensities given by Alburger and Pryce [3] relative internal conversion coefficients were found for 20 transitions in Pb^{206}. The multipolarity assignments thus obtained were in most cases in agreement with those given by Alburger and Pryce.

The present investigation was started in order to get a further check on the complex decay schemes of Bi^{205} and Bi^{206} by studying internal and external conversion with a thin radioactive source of $Bi^{205} + Bi^{206}$ (or with two sources of known relative strengths). From these data *absolute* values of the internal conversion coefficients were obtained according to the procedure of analysis described by Hultberg and Stockendal [6]. In this connection the superiority of internal conversion coefficients to conversion ratios as a tool for multipolarity determinations in this Z-region, especially for high energies, should be emphasized.

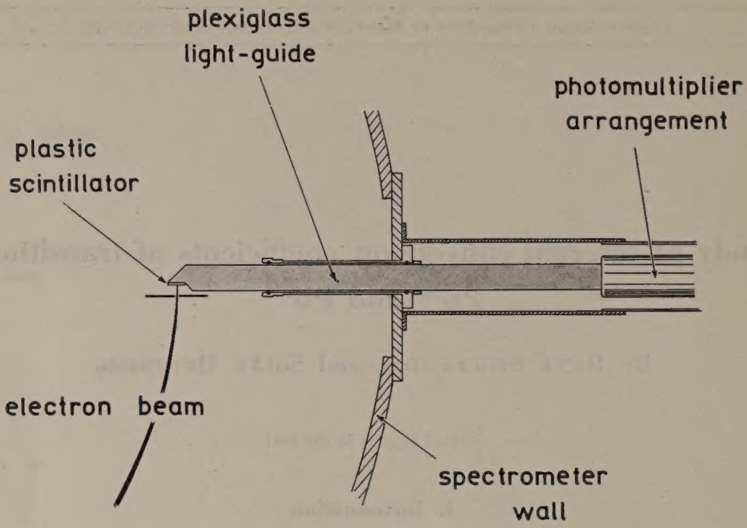

Fig. 1. Schematic view of the crystal detector arrangement used in some of the measurements on internal and external conversion (cf. Figs. 2 and 3).

2. Experiments

1. *Source preparation*

The active $Bi^{205}+Bi^{206}$ was produced by bombarding radiogenic lead (88 % Pb^{206}, 9 % Pb^{207} and 3 % Pb^{208}) with 23 MeV deuterons in the 225 cm cyclotron of the Nobel Institute. In order to obtain a strong source—an essential condition in experiments with external conversion—the irradiation was carried out during a period of about 200 hours with a beam current of 20–25 μA. At the end of the bombardment the produced bismuth activity scraped off the target was found to give a dose rate of 1 r/h at 250 cm. The chemical separation of the bismuth from the target material was carried out using techniques which have been described elsewhere [7, 1]. Two beta-spectrometer sources of circular shape with 0.6 cm diameter were then prepared by electroplating onto thin Cu foils (cf. refs. [7] and [1]). The dose rate from the stronger sample was 1 r/h at 120 cm immediately after the preparation, while the other sample was about 16 times weaker.

2. *Beta-spectrometer measurements*

The experiments were carried out in a double-focusing beta-spectrometer [8]. The procedure of measurements was the following (for details, see ref. [6]):

Firstly, the photoline spectrum from a plane uranium converter was measured. A 0.1 cm thick aluminium plate was placed between the source and the converter for absorbing the internal conversion electrons. The uranium converter, containing 2.19 ± 0.02 mg U/cm², was circular with a diameter of 1.46 cm. As to the preparation of the uranium converter, see ref. [5].

Secondly, the uranium converter and the absorber were removed, and the internal

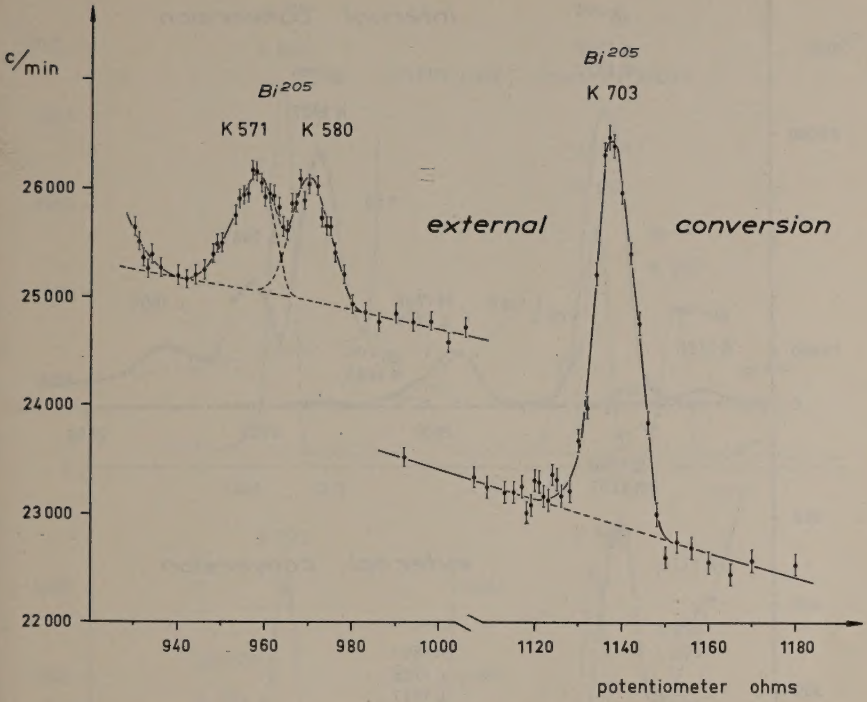

Fig. 2. External conversion lines measured at about 1 % resolution in the double-focusing spectrometer with the scintillation equipment (schematically shown in Fig. 1) as detector. A 2.19 mg/cm² U-converter was used. The statistical errors are indicated. No decay corrections have been performed.

conversion-line spectrum was measured with the source taking the position of the converter.

To start with, a GM-counter was used as a detector in the spectrometer. It soon became evident, however, that when using the same source for internal and external conversion, the arrangement had disadvantages because of the enormous counting rates on some of the internal conversion lines, resulting in large and uncertain corrections for the dead-time of the GM-counter. The ratio between the counting rates in internal and external conversion with the same source were often of the order of 100. To solve the problem, two ways were tried: (*a*) The GM-counter was replaced by a scintillation crystal equipment (see description below); (*b*) The GM-counter remained as detector, but two samples of different source strengths were used, the stronger one for external conversion and the weaker one for internal conversion.

(*a*) *Measurements with a scintillator as an electron detector*

Fig. 1 shows schematically the crystal detector arrangement. The 0.2 cm thick plastic scintillator was rectangular (2.0 × 2.8 cm) and fastened to a 49 cm long

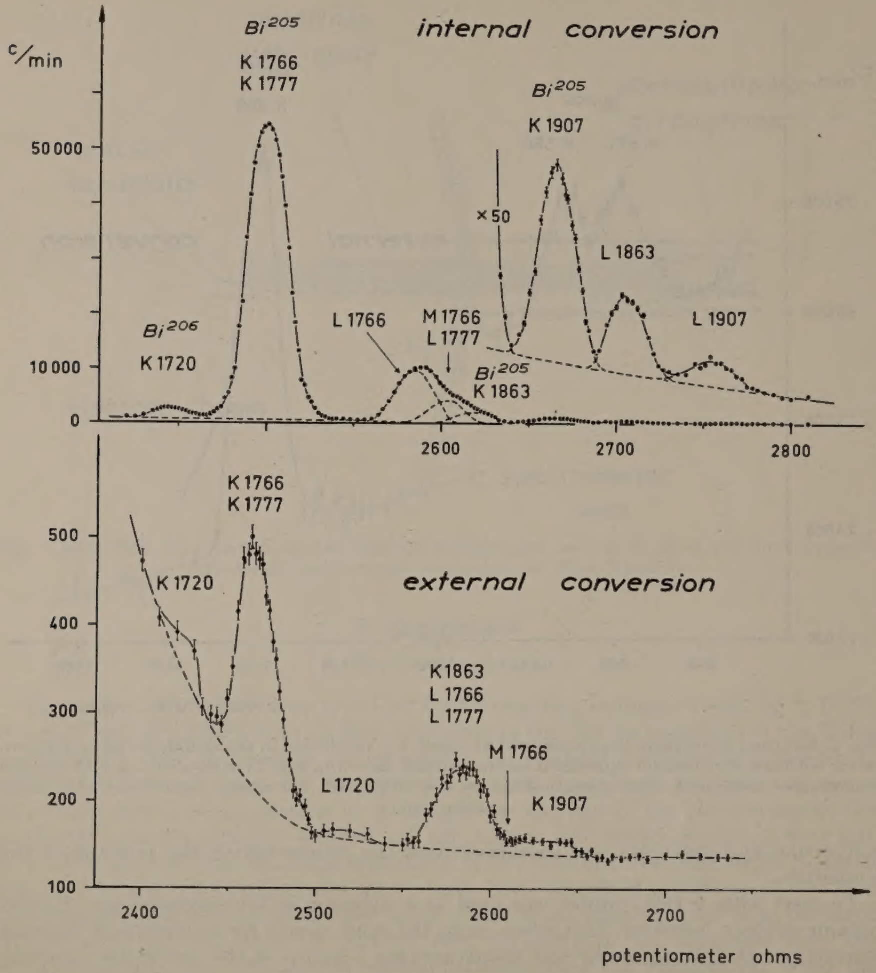

Fig. 3. Some internal (upper curves) and external (lower curves) conversion lines, as measured with the *same* source in a double-focusing spectrometer with the scintillation equipment of Fig. 1 used as electron detector. The resolution is about 1 %. The statistical errors are shown. Decay corrections have not been carried out. The figure illustrates the large variations in line intensities. The conversion coefficients of the 1720, 1766 and 1777 keV transitions were obtained with the aid of measurements with higher resolution (0.4 %).

cylindrical light-guide of plexi-glass. 24 cm outside the spectrometer wall the light-guide was connected to a photomultiplier surrounded with μ-metal. The resolving time of the crystal was of the order of 2 μsec, i.e. approximately 100 times smaller than for the GM-tube. With this arrangement the dead-time corrections of the measured counting rates became negligible.

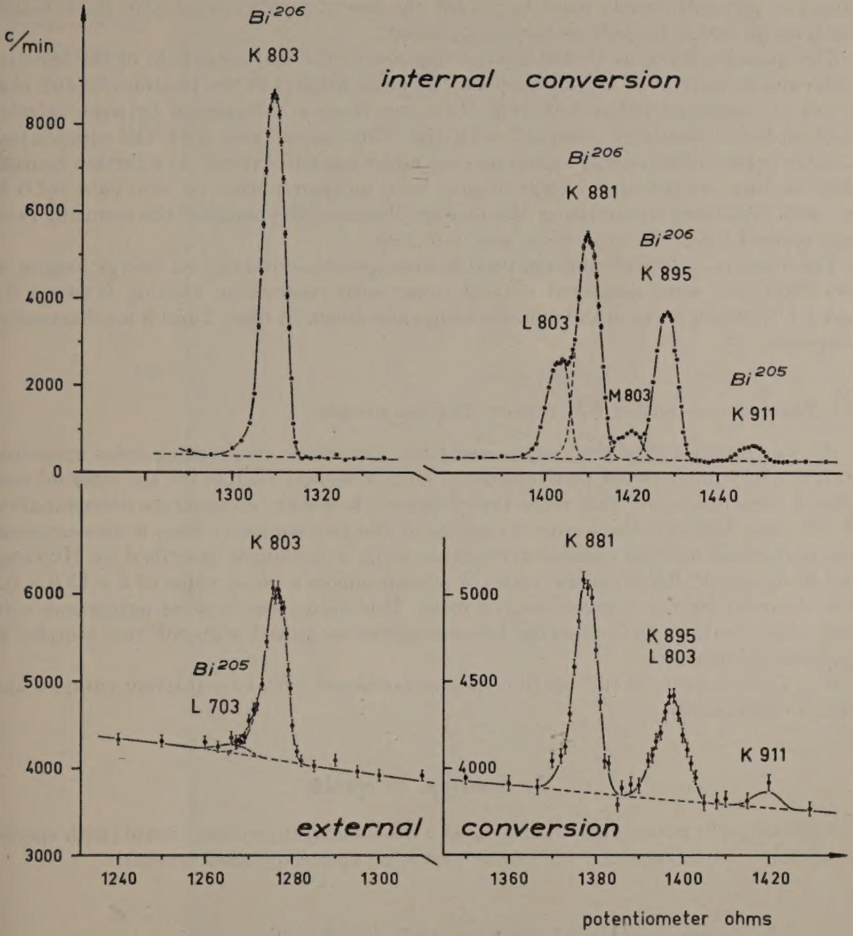

Fig. 4. Parts of the internal (upper curves) and external (lower curves) conversion-line spectra of Bi^{206}, as measured at about 0.45 % resolution with two identically prepared sources of known relative source strengths ($k_\gamma / k_\beta = 15.9$) and with a GM-counter used as detector. The statistical errors are indicated. No decay corrections have been made.

The scintillation equipment was operated in a manner analogous to the performance of a GM-counter, i.e. all pulses surpassing a preset discriminator level were recorded as counts. For electron energies above 150 keV the light pulses produced by the electrons could readily be separated from the noise level of the photomultiplier, which means that a range of discriminator voltages could be found where the counting rate remained constant (equivalent to the plateau of a GM-counter). The homogeneity in pulse heights for the nearly monoenergetic electron beam in the spectrometer was, however, not sufficiently good to permit the use of a differential gate pulse-height analyzer in order to depress the background.

The question arose as to whether an increase of the magnetic field of the spectrometer might have such an influence on the pulse heights in the photomultiplier that a loss of registered pulses followed. However, from a comparison between relative electron-line intensities obtained with the GM-counter and with the scintillation counter in the actual energy region no such effect was discovered. As a further control, electron lines in the high energy region were measured with an iron tube (of 0.35 cm wall thickness) surrounding the photomultiplier. No change of the counting rates was noticed when the iron tube was removed.

The internal and external conversion-line spectra, covering an energy region of 200–2800 keV were measured several times with resolutions varying between 0.4 and 1.1 %. Small parts of the measurements are shown in Figs. 2 and 3 for illustrative purposes.

(*b*) *Measurements with a GM-counter and two samples*

As was mentioned above, large dead-time corrections of counting rates measured with a GM-counter could be avoided by using a weaker sample for the internal conversion measurements. This procedure required, however, an accurate determination of the ratio between the source strengths of the two samples. Such a measurement was performed with an ionization chamber using a technique described by Hultberg and Hedgran [9]. From several series of measurements a mean value of $k = 15.9 \pm 0.3$ was obtained for the source-strength ratio. This value was in good agreement with the value obtained by comparing line intensities measured with the two samples in the beta spectrometer.

Fig. 4 shows parts of the electron spectra measured with two different samples and with a GM-counter.

3. Analysis of results

Following the notation by Hultberg and Stockendal [6] we may write (with special application to internal K-conversion electrons and K-photoelectrons):

$$\varepsilon_K = \frac{A_\beta}{A_\gamma}\,\tau_K\; f\; d\; k\; b,$$

where

ε_K	internal K-conversion coefficient
A_β	recorded intensity of internal K-conversion electrons
A_γ	recorded intensity of K-photoelectrons
τ_K	tabulated value of photoelectric cross-section for the K-shell [11]
f	correction factor for τ_K (see ref. [6])
d	converter thickness
k	relative source strength $= k_\gamma/k_\beta$
b	dimension factor

For a detailed discussion of the formula the reader is referred to ref. [6].

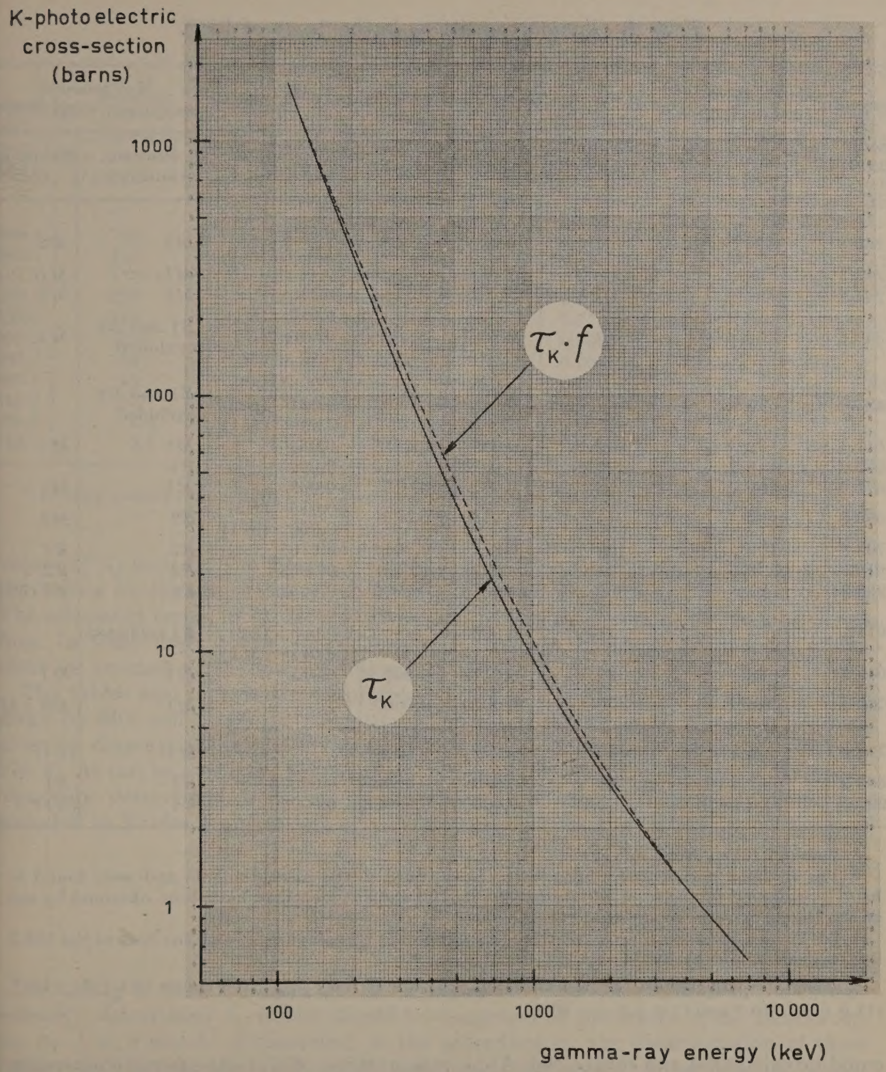

Fig. 5. The tabulated photoelectric cross-sections for the K-shell of uranium (τ_K) and the photoelectric cross-sections ($\tau_K \cdot f$) to be applied to the analysis of the photolines of Pb^{205} and Pb^{206}. $\vartheta_0 = 78°$ (see ref. [6]).

A_β and A_γ were represented by the areas under the measured electron lines, corrected for momentum and decay. In a few cases the K-photoline of one gamma ray was mixed with the L-photoline of another gamma ray. Then, from the K-intensity and K/L ratio in the external conversion of the latter gamma ray the L-contribution

Table 1. Gamma transitions in the decay of Bi^{205}.

Gamma-ray energy[1] (keV)	Relative internal K-conversion line intensity I_β ($I_{K703.3} = 100$)	Relative gamma-ray intensity I_γ ($I_{\gamma\,703.3} = 100$)	Internal K-conversion coefficient ε_K		Multipolarity assignment suggested b	
			Experimental	Theoretical (Sliv & Band)	Present authors	Schmoral *et al.*
260.5	170	4.4	0.43 ± 0.06[3]	0.51 ($M1$) 1.9 ($M2$)	$M1$	$M2$
282.3	50[2]	5.4	0.49 ± 0.08[3]	0.41	($M1$)	$M1$
284.2	190[2]			0.41	$M1$	$M1$
349.4	30	< 3.3	> 0.10	0.017 ($E1$) 0.046 ($E2$) 0.23 ($M1$)	$E1$ and $E2$ excluded	$M1$
493.6	11[1]	< 2.8	> 0.04	0.0081 ($E1$) 0.021 ($E2$) 0.090 ($M1$)	$E1$ and $E2$ excluded	
511.7	22[1]	≈ 3	0.08 ± 0.04	0.084	$M1$	$M1$
550.0	6.3	9.6	0.0072 ± 0.0015	0.0065	$E1$	
571.0	89	16	0.061 ± 0.015	0.063	$M1$	$M1$
580.0	24	17	0.015 ± 0.003	0.015 ($E2$) 0.060 ($M1$)	$E2$	$M1$
703.3	100	100	0.011 ± 0.001[4]	0.0105	$E2$	$E2$
910.8	8.4	14	0.0066 ± 0.003	0.0063	$E2$	$E2$
987.8	27	60	0.0049 ± 0.0009	0.0054	$E2$	$E2$ ($E1$)
1014.2	4.9[1]	< 11	> 0.005	0.0020 ($E1$) 0.0052 ($E2$) 0.014 ($M1$)	$E1$ excluded	
1043.7	28	27	0.011 ± 0.002	0.013	$M1$	$M1$
1766.4	34	96	0.0039 ± 0.0007	0.0035 ($M1$) 0.0019 ($E2$)	$M1$	$E2(+M1$
1777.4	4.0	≈ 10	$0.004\ ^{+0.0025}_{-0.0015}$	0.0034 ($M1$) 0.00078($E1$)	($M1$)	($E1$)
1863.3	1.3	21	0.00069 ± 0.0003	0.00073	$E1$	$E1$
1906.5	0.40	7.1	0.00063 ± 0.00025	0.00070	$E1$	($E1$)

[1] Value(s) taken from ref. [1].

[2] The K 282.3 and K 284.2 lines were not resolved in the measurements and were found to have a combined intensity of 240 units. The partial values given here have been obtained by use of the intensity ratio reported in ref. [1].

[3] Coefficient obtained from a "relative" measurement by comparison with the lines of the 703.3 keV transition and by setting $\varepsilon_{K\,703.3} = 0.011$.

[4] Using the coincidence method Gerholm [13] found for $\varepsilon_{K\,703.3}$ the values $(8.4 \pm 1) \times 10^{-3}$, $(11.0 \pm 3) \times 10^{-3}$ and $(7.5 \pm 2.5) \times 10^{-3}$.

could be calculated and subtracted. Appropriate values of K/L in external conversion were obtained from a recent investigation by Hultberg and Sujkowski [10] on the angular dependance of L and $(M+N+\ldots)$ shell photoelectrons and its energy variation.

Tables 1 and 2 give the results obtained for the transitions in Pb^{205} and Pb^{206}, respectively. The values of I_β, I_γ and ε_K are mean values from several runs and have been calculated by use of $b = 2.531 \times 10^{-6}$ (for uranium), $d = 2.19 \pm 0.02$, $k = 1$ or 15.9 ± 0.3, the values of τ_K given by White Grodstein [11] combined with the values of f found by Hultberg and Stockendal [6] (see Fig. 5), and the experimental

Table 2. Gamma transitions in the decay of Bi^{206}.

amma-ray nergy[1] (keV)	Relative internal K-conversion line intensity I_β ($I_{K803.3} = 100$)	Relative gamma-ray intensity I_γ ($I_{\gamma\,803.3} = 100$)	Internal K-conversion coefficient ε_K		Multipolarity assignment suggested by	
			Experimental	Theoretical (Sliv & Band)	Present authors	Alburger & Pryce
343.4	760	26	0.25 ±0.03	0.24	$M1$	$M1$
398.1	210	10	0.18 ±0.02	0.16	$M1$	$M1(+E2)$
497.1	170	18	0.081 ±0.015	0.090	$M1$	$M1(+E2)$
516.1	250	46	0.047 ±0.005	0.049	$E3$	$E3$
537.5	280	34	0.070 ±0.008	0.073	$M1$	$M1(+E2)$
803.3	100	100	0.0086 ±0.0009	0.0081	$E2$	$E2$
880.5	60	73	0.0071 ±0.0010	0.0068	$E2$	$E2$
895.1	44	19	0.020 ±0.005	0.020	$M1$	$M1(+E2)$
1018.8	15	≈ 8	0.016 ±0.008	0.014	$M1$	$M1(+E2)$
1098.6	2.8	13	0.0019 ±0.0005	0.0018	$E1$	$E1$
1719.7	3.4	36	0.00082 ± 0.00015	0.00082	$E1$	$E1$

[1] Energy values taken from ref. [3].

values of A_β and A_γ. The intensity values I_β and I_γ have been normalized by setting the values for the transitions of 703.3 keV (Pb^{205}) and 803.3 keV (Pb^{206}) equal to 100. The estimated errors in ε_K are also given and will be discussed in the following section. In some cases it was possible only to set a lower limit to the conversion coefficient on account of the low photoline intensity.

The tables also include the theoretical values of the K-conversion coefficients ε_K given by Sliv and Band [12]. For convenience the experimental ε_K-values are also given in diagrammatical form together with the theoretical curves for $Z = 82$ (see Fig. 6). As can be seen from this diagram, multipolarities can, in most cases, be unambiguously determined from the K-conversion coefficients. The assignments are included in Tables 1 and 2.

4. Discussion of results

1. *Error in* ε_K

According to the formula in the preceding section the uncertainties in the experimentally determined ε_K-values should be composed of the errors in the factors A_β, A_γ, τ_K, f, d, k and b. A discussion of the procedure for the determination of these errors was given in the work by Hultberg and Stockendal [6], with special application to the case of the 662 keV transition in the decay of Cs^{137}. In accordance with the quoted paper we set the errors of τ_K, f, d and b equal to 6 %, 5 %, 1 % and 0, respectively. The error in k (which is either exactly 1, or 15.9 ± 0.3) is 0 or 2 %. Due to the complexity of the electron-line spectra the largest error arises from the determination of A_β/A_γ (in contrast to the more favourable Cs^{137}-case). Because of the variation in line intensities in the spectra or due to the eventual occurrence of overlapping, this error is found to take values between 7 and 50 % in the different cases. A survey of the errors is given in Table 3.

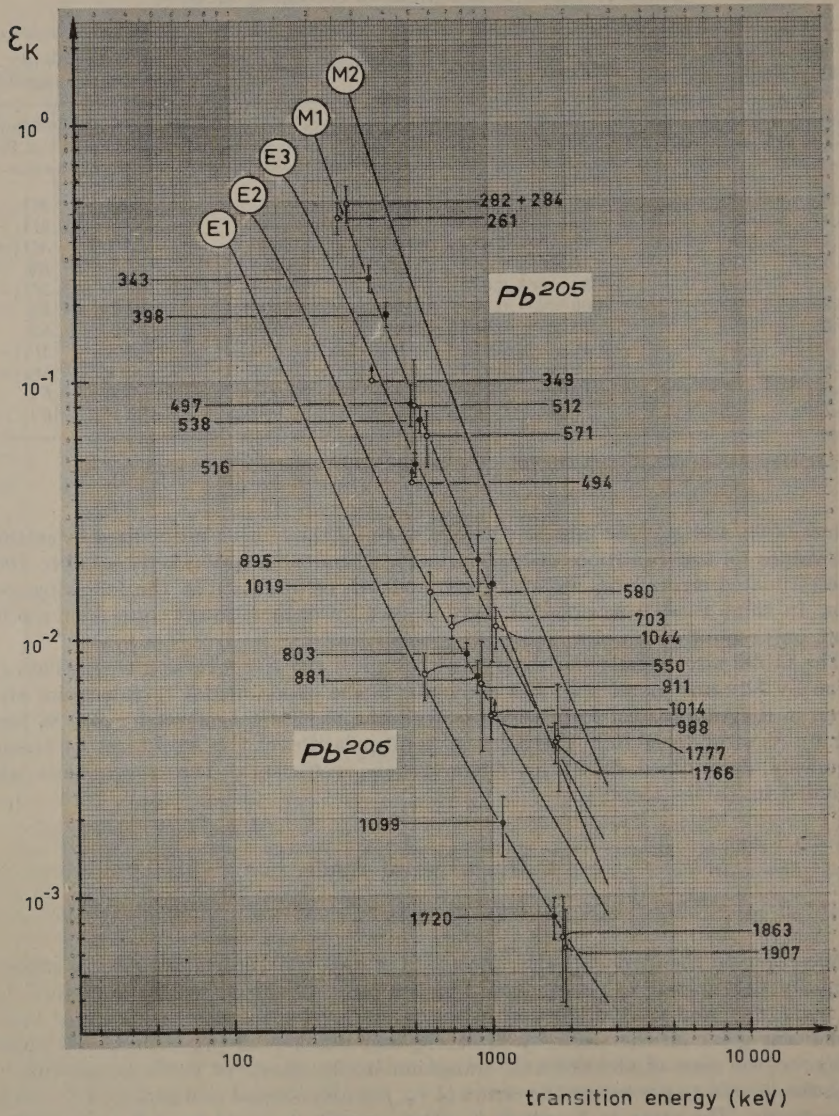

Fig. 6. Comparison between theoretical conversion coefficients of Sliv and Band for $Z = 82$ (curves) and experimental values for transitions in Pb^{205} (circles, transition energies in keV given to the right) and Pb^{206} (points, transition energies given to the left). The arrows used for the 349, 494 and 1014 keV transitions indicate lower limits of ε_K.

Table 3. Contributions to the error of ε_K.

Source of error	Estimated error (in %)
A_β/A_γ	Varying between 7 and 50
τ_K	6
f	5
d	1
k	0 or 2
b	0

It should be mentioned that the error given for A_β/A_γ also includes a small uncertainty ($<1\,\%$) entering in the decay-corrections of the electron lines. The half-life of Bi^{205} has been measured as 14.5 days (no limits of error reported) [14] and 15.3 ± 0.7 days [2]. For Bi^{206} the available data are 6.35 ± 0.2 days [15] and 6.30 ± 0.12 days [16]. In our decay-corrections the values 15.0 and 6.30 days were taken for the Bi^{205} and Bi^{206} lines, respectively. Since the time interval between the measurements of an internal conversion line and the corresponding photoline generally was a few days, the uncertainty arising from *one* series of measurements should be well below 2 %. However, since the lines were measured in the opposite order in another series, the mean value of A_β/A_γ obtained from one or several such couples of series is relatively insensitive to the error in the half-life.

By quadratical addition of the errors presented in Table 3 the uncertainties of ε_K given in Tables 1 and 2 and in Fig. 6 have been obtained. From an inspection of these uncertainties it is clear that the conversion coefficients of Bi^{206} in general are more accurately determined than those of Bi^{205}. This is due mainly to the fact that, in the first measurements, the attention was concentrated on the dominating 6.3 *d* Bi^{206} spectrum. Most of the 15 *d* Bi^{205} lines, however, necessarily had to be measured one or two months later when the $\mathrm{Bi}^{205}/\mathrm{Bi}^{206}$ ratio was more favourable. Thus the intensities of these lines were in general smaller than in the case of Bi^{206}, resulting in lower accuracy of the ε_K-values.

2. *Multipolarity assignments*

As can be seen from Tables 1 and 2 the suggested multipolarity assignments are in most cases in agreement with those given by Schmorak *et al.* [1] (Pb^{205}) and by Alburger and Pryce [3] (Pb^{206}). Only in the cases of the 260.5, 580.0, 1766.4 and 1777.4 keV gamma rays in Pb^{205} are the multipolarity assignments different.

The 260.5 keV transition was suggested by Schmorak *et al.* to have $M2$ character $[K/(L_{\mathrm{I}} + L_{\mathrm{II}}) = 3.4 \pm 0.6$ and $L_{\mathrm{I}}/L_{\mathrm{II}} = 5^{+4}_{-2}]$, whereas Fritsch [2] suggests $M1$ on the basis of L-subshell conversion. The value $\varepsilon_K = 0.43 \pm 0.06$ found in the present investigation clearly indicates $M1$ with a possible admixture of $E2$ [cf. the theoretical values by Sliv and Band [12]: 0.51 ($M1$) and 1.9 ($M2$)]. Thus, the K/L ratio quoted above might be in doubt. Accurate measurements of the K- and L-conversion lines were therefore performed repeatedly and gave as a result $K/L_{\mathrm{I}} + L_{\mathrm{II}}) = 5.8 \pm 0.5$ (L_{III}-line overlapped) [cf. the theoretical values of Rose [17]: 6.3 ($M1$) and 3.9 ($M2$)]. It must therefore be concluded that the 260.5 keV transition is mainly of multipolarity $M1$. In this connection it may be noticed that, according to recent alpha-

and gamma-ray data of Asaro and Perlman [18] on the decay of Po^{209}, the first excited state of Pb^{205} lies at 260 ± 2 keV. Furthermore, from conversion coefficient information, the 260 keV transition deexciting this state is by these authors considered to be magnetic dipole. It is therefore tempting to believe that this transition is identical with the 260.5 keV transition observed in the decay of Bi^{205}.

For the *580.0 keV transition* our value $\varepsilon_K = 0.015 \pm 0.003$ would indicate the multipolarity $E2$ [theoretical values [12]: 0.015 ($E2$) and 0.060 ($M1$)]. Schmorak *et al.* found $M1$ more probable from $\varepsilon_K > 0.03$, estimated from the scintillation spectrum, and $K/L = 7.0 \pm 2.5$. A check of the latter value, however, revealed an interpretation mistake, and the correct information from this measurement should be $K/(L_{\mathrm{I}} + L_{\mathrm{II}}) = 5.1 \pm 2.0$. Hence an $E2$ assignment on this basis is quite possible [cf. theoretical values [17]: 4.0 ($E2$) and 6.2 ($M1$)]. Of the available data on ε_K the value obtained by the method of internal and external conversion must be considered far more reliable, since the photolines of the 571.0 and 580.0 keV gamma rays were almost completely resolved (see Fig. 2).

As to the *1766.4 and 1777.4 keV transitions*, Schmorak *et al.* obtained the best fit between the K-line intensities (K 1766.4/K 1777.4 = 8.4) and the combined gamma-ray intensity by assuming multipolarities $E2$ (with a possible admixture of $M1$) and $E1$, respectively. This result should, however, be taken with some reservation with regard to the uncertainties involved in an estimation of gamma-ray intensities from a scintillation spectrum. From the value $\varepsilon_K = 0.0039 \pm 0.0007$ obtained in the present investigation for the 1766.4 keV transition, an $M1$ assignment seems certain [cf. theoretical values [12]: 0.0035 ($M1$) and 0.0019 ($E2$)]. This assignment also fits the decay scheme of Schmorak *et al.* very well, since the 1766.4 keV transition is suggested to take place from a $7/2-$ state to the $5/2-$ ground state. The information on the 1777.4 keV transition is not so accurate because of the low photoline intensity, but $M1$ seems to be the most probable assignment for this transition as well (cf. Fig. 6). It should be pointed out that the tabulated data were obtained by aid of a measurement with the 1766.4 and 1777.4 keV lines well resolved (not resolved in Fig. 3, however).

The lines of the *282.3 and 284.2 keV transitions* were not resolved in the measurements and the tabulated conversion coefficient $\varepsilon_K = 0.49 \pm 0.08$ has therefore been obtained from the combined conversion and photoline intensities. From this value, however, it seems certain that the dominating 284.2 keV transition is of multipolarity $M1$. It is not possible to draw any definite conclusions about the 282.3 keV transition, but $M1$ seems most probable. Schmorak *et al.* [1] found $M1$ in both cases.

For some gamma rays only lower limits of ε_K could be obtained because of the small photoline intensities. In three of these cases, namely the *349.4, 493.6 and 1014.2 keV transitions* in Pb^{205}, the limits had significant values (cf. Table 1 and Fig. 6). Thus, for the 349.4 and 493.6 keV transitions the multipolarities $E1$ and $E2$ should be excluded, while the limit in the case of the 1014.2 keV transition excludes only $E1$. The $M1$ assignment suggested for the 349.4 keV gamma ray by Schmorak *et al.* is thus consistent with our information.

In the case of the *537.5 keV transition* in Pb^{206} Alburger and Pryce [3] assumed an $M1 + E2$ mixture in the ratio 5 to 3 in order to obtain a proper intensity balance in the decay scheme. However, if the theoretical conversion coefficients of Sliv and Band [12] are used in the calculation of the transition intensities the $E2$ admixture is found to be only about 15 %. On the other hand, Novakov *et al.* [5] found an $M1 + E2$ mixture in the ratio 1 to 1 from the measured value $\varepsilon_K = 0.047$ [cf. the theoretical values [12]: 0.073 ($M1$) and 0.018 ($E2$)]. In order to resolve this inconsistency particular attention was paid, in the present investigation, to the measurements of the photolines of the 537.5 keV transition. The mean value from six runs was found to be $\varepsilon_K = 0.070 \pm 0.008$. The maximum $E2$ admixture which can be calculated from this result is about 20%, which is thus consistent with the recalculated value from the data of Alburger and Pryce.

When comparing the present determinations of relative gamma-ray intensities for transitions in the decay of Bi^{206} (Table 2) with those given by Novakov *et al.* [5], it should be mentioned here that due to an error of systematic character in the analysis of the measured photolines ($J(\vartheta + \Delta) \sin \vartheta$ was used in Eq. (5) of ref. [6] instead of the correct $J(\vartheta + \Delta) \operatorname{tg} \vartheta$) the gamma-ray intensities of Novakov *et al.* should be decreased by about 20% at 300 keV, 10% at 400 keV and 0% at 700 keV and above. This correction will increase ε_K and will generally improve the agreement between the relative ε_K-values given and the theoretical values. The multipolarity assignments deduced will thus remain unchanged.

APPENDIX

High-energy lines in the decay of Bi^{205}

In the investigation of Bi^{205} by Schmorak *et al.* [1] the photo peak of a 2600 ± 50 keV gamma ray was observed in the scintillation spectrum. Experiments with a hollow crystal revealed a considerable coincidence effect of gamma rays, the energies of which sum up to about 2.6 MeV. In agreement with this conclusion are the following gamma-ray energy relations (in keV) indicating an excited state of 2566.5 keV:

$$\begin{aligned} 1863.3 + 703.3 &= 2566.6 \\ 1014.2 + 1552.0 &= 2566.2 \\ 511.7 + 1351.5 + 703.3 &= 2566.5 \\ 511.7 + 349.4 + 1002.7 + 703.3 &= 2567.1 \\ \text{energy of cross-over gamma ray} &= 2600 \pm 50. \end{aligned}$$

Further support of this state was obtained from electron-gamma coincidence measurements showing that the 703.3 keV transition is in coincidence with the 1863.3 and/or 1906.5 keV gamma rays. Finally, Vegors and Heath found coincidences between the 703.3 keV gamma ray and a gamma ray of about 1870 keV [19].

However, the internal conversion lines of the high energy gamma ray were, because of their weakness, not observed in the measurements in the double-focusing spectrometer [1]. It was hoped therefore that with the stronger source available in the present work it would be possible to detect these conversion lines. The result of a measurement in this energy region with the double-focusing spectrometer is shown in Fig. 7. The spectrum, which was shown to decay with the Bi^{205} half-life, is interpreted as K 2567.8, K 2610.0 and L 2567.8. Table 4 gives the mean values of energies and intensities obtained from four runs. The K 1766.4 and K 1906.5 lines[1] were used for the energy calibration.

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[1] As an additional result the following data were obtained for the 1906.5 keV transition $I_{K\,1906.5} = 0.40 \pm 0.10$ ($I_{K\,703.3} = 100$), and K/L 1906.5 $= 6.5 \pm 1.0$.

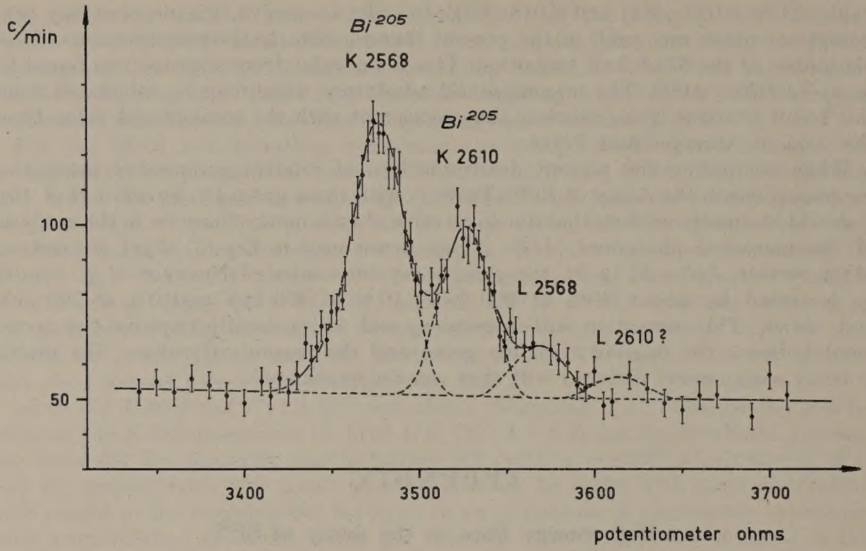

Fig. 7. Internal conversion lines of the weak 2.6 MeV gamma rays following the decay of Bi^{205}. The statistical errors are shown.

Table 4. High-energy gamma rays in the decay of Bi^{205}.

Measured gamma-ray energy (keV)	Relative K-line intensity ($I_{K\ 703.3} = 100$)	K/L
2567.8 ± 2.0	0.029	5.9 ± 2
2610.0 ± 2.0	0.016	—

A measurement with the purpose to find the external conversion lines of the 2.6 MeV gamma rays was also carried out, but no lines were detected. The lower limits of ε_K thus obtained were not significant for multipolarity determination.

It is obvious that the photo peak at 2.60 MeV, seen in the scintillation spectrum, is due to the two gamma rays presented in Table 4. The 2567.8 keV gamma ray thus detected from its K- and L-conversion lines is very probably identical with the gamma ray emitted directly to ground from the above-mentioned state of 2566.5 keV (9/2 (+)). The energy agreement is better than 1:1000. Since the total decay energy of Bi^{205} is found to be 2.65 ± 0.03 MeV [1], the gamma ray of 2610.0 keV should be emitted from a state of this energy directly to the Pb^{205} ground state. The energy relations (in keV)

$$1906.5 + 703.3 = 2609.8$$
$$\text{energy of cross-over gamma ray} = 2610.0$$

suggest that the 2610 keV state is deexcited also by the 1906.5 keV transition populating the 9/2 − (or 7/2 −) state of 703.3 keV. If this be the case, the most probable spin and parity assignment of the 2610 keV state should be 7/2 +, 9/2 + or 11/2 + because of the suggested multipolarity $E1$ of the 1906.5 keV transition (see Table 1) and the 9/2 − ground state of Bi^{205} (spin value 9/2 recently established by Lindgren [20], using atomic-beam resonance techniques).

The above suggestions regarding the 2610 keV state seem to be well understood from the theoretical works of Pryce [4] and True [21]. It may be noticed that the formerly suggested position of the 1906.5 keV E1 transition going directly to the ground state from an excited state of 1906.5 keV [1] is in disagreement with theory, since no state having even parity and spin value 3/2, 5/2 or 7/2 is predicted in this energy region.

SUMMARY

Relative intensities of 14 gamma rays following the decay of Bi^{205} and 11 gamma rays from the decay of Bi^{206} have been measured by the method of external conversion in uranium. From additional measurements of the internal conversion lines from the same source (or from a source of known relative source strength) the K-conversion coefficients of these gamma transitions have been determined *absolutely* with an accuracy varying between 10 and 50 %. The multipolarity assignments based on these values are in most cases in agreement with those suggested from scintillation spectra and internal conversion-line spectra.

Further support of the excited state of 2566.5 keV in Pb^{205} has been found from the detection of the K- and L-conversion lines of a 2567.8 ± 2.0 keV transition. The K-conversion line of a 2610.0 ± 2.0 keV gamma ray has been detected suggesting an excited state of this energy.

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